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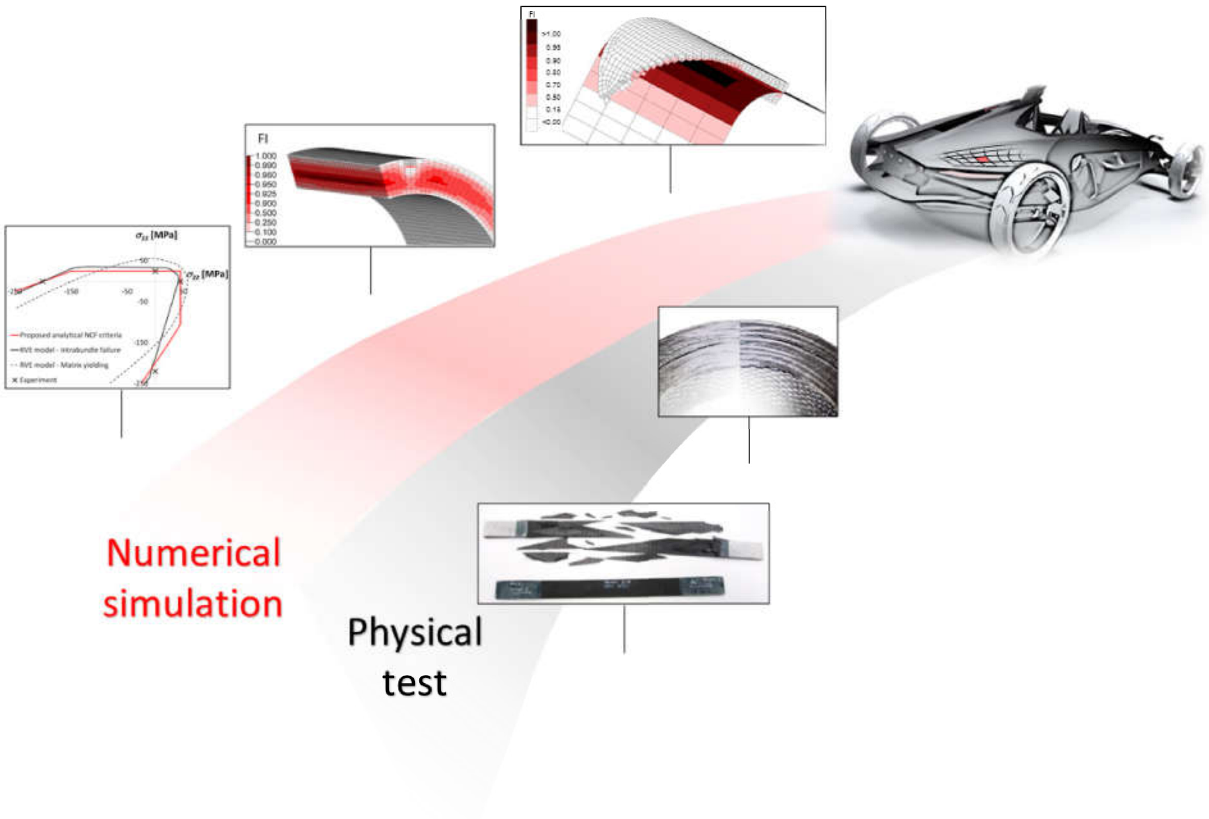

Industrial framework for hot-spot identification and verification in automotive composite structures

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CHALMERS UNIVERSITY OF TECHNOLOGY

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Cover:
Framework for efficient analysis of automotive composite structures by employing sub-modelling of hot-spots found in global models. Visualised on the Volvo Air Motion Concept. For more details, see chapter 1.

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Abstract

The automotive industry needs to reduce energy consumption to decrease environmental impact from greenhouse gases. This can be achieved by reducing the weight of cars. A promising way to lower the weight of automotive primary structures is to introduce carbon fibre composites, as they have outstanding specific properties. However, current car development relies on virtual environment while composite designs are still based on testing. To introduce composite materials in primary automotive structures, industry needs an efficient design methodology that can be used in virtual development processes. In addition, the automotive industry needs new material systems and production methods to produce composite structures in high volumes and at profitable cost.

In this thesis, an efficient and reliable design methodology for automotive composites structures is proposed. The methodology combines numerical models at multiple scales. Firstly, potential hot-spots are identified in a global analysis. In a second operation, these are analysed using high fidelity local models. Both the global and the local models are adapted to consider all prevailing failure modes in the composites of use.

A likely material system for use in automotive primary structures is Non-Crimp Fabric (NCF) reinforced composites. In contrast to traditional tape-based Uni-Directional (UD) reinforced composite materials, which are transversely isotropic, NCF composites are not. Instead NCF composites have been found to be orthotropic. Available failure initiation criteria are based on the assumption of transverse isotropy. In this thesis, a new set of criteria for assessing failure initiation of orthotropic NCF reinforced composite materials is proposed. The failure criteria are compared and verified against data from literature and numerical models. The set of criteria have also been implemented into a commercial finite element code and verified against physical experiments.

Keywords: Analysis framework; Global - local; Sub-modelling; Carbon fibre composite; Non crimp-fabric; Failure initiation; Orthotropic material

Preface

During 10 years of work within finite element simulations in one way or another, there has always been a thought about the possibilities of doing a PhD. From time to time more pronounced. However, as time goes by life changes and one gets more settled in.

Who would guess that my wife, by chance, would find a job advert with the title ”*Industrial Ph.D. Candidate - CAE for composite structures*”. – Does not this include all the key and buzzwords that you have mentioned from time to time? And frankly, it did. Together with the fact that it was in the city that we recently moved back to made the choice even easier. Now, looking back, I am very happy to have gotten this opportunity.

This project is funded by the Volvo Industrial PhD Program (VIPP) and the Swedish Research Council (VR) 2012-4320, whose financial supports are gratefully acknowledged. The work has been carried out at Volvo Cars in Göteborg with periods at Rise Sicomp AB in Mölndal and Chalmers University of Technology in Göteborg during the project. A short but important part of the work was carried out at Imperial College in London at the Aeronautics department.

Without the guidance and support from my supervisors Prof. Leif Asp and Dr. Renaud Gutkin the work would not have been as successful, or fun, as it has been. Leif for painting the background and large structures of composites on my composite picture with an airbrush and Renaud for clarifying things with the fine brush and for highlighting the details. In addition, Prof. Silvestre Pinho at Imperial College has added lighting to the picture from another perspective. All together I think that we have accomplished some nice pieces of work with this thesis as the crown jewel. Also, a thank you to Dr. Magnus Oldenbo who initiated this project at VCC and made all the hard work to make it happen and giving me a canvas on an easel to start with.

I would also like to thank my colleagues at VCC and Dr. Annika Lundberg for getting me into the automotive world, and to understand the demands and needs thereof and for a nice atmosphere to work in. Also a thank you for the discussions within the group of Lighweight and materials and Structures at Chalmers and in the early years the discussions at Rise Sicomp in Mölndal.

Finally for the support and understanding from my wife Anna and our kids Erik and Axel. For allowing me to get back, at least partially, to academia, with study periods, deadlines and times of writing. And to my parents, brother and parents in law for your never-ending support and belief in me.

Göteborg January 2019

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I "Orthotropic criteria for transverse failure of non-crimp fabric reinforced composites"
Molker, H., Wilhelmsson, D., Gutkin, R. & Asp, L. E.
Journal of Composite Materials. 50(18), pp. 2445-2458, 2015.
doi: 10.1177/0021998315605877

Molker developed the analytical criteria and compared to existing data. Wilhelmsson developed the meso-scale model and the post-processing for the numerical simulations with the representative volume element. Molker wrote the paper together with Wilhelmsson with assistance from Gutkin and Asp.

II "Implementation of failure criteria for transverse failure of orthotropic Non-Crimp Fabric composite materials"
Molker, H., Gutkin, R. & Asp, L. E.
Composites Part A: Applied Science and Manufacturing. 92, pp. 158-166, 2016.
doi: 10.1016/j.compositesa.2016.09.021

Molker made the implementation and performed the experimental tests. Molker wrote the paper with assistance from Gutkin and Asp.

III "Hot-spot Analysis in complex composite material structures"
Molker, H., Gutkin, R., Pinho, S. & Asp, L. E.
Composite Structures. 207, pp. 776-786, 2019.
doi: 10.1016/j.compstruct.2018.09.088

Molker proposed the approach and made the implementation. Molker wrote the paper with assistance from Gutkin, Pinho and Asp.

IV "Industrial framework for identification and verification of hot-spots in automotive composite structures"
Molker, H., Gutkin, R. & Asp, L. E.
Submitted manuscript

Molker proposed the set-up of the framework and performed the implementation. Molker wrote the paper with assistance from Gutkin and Asp.

V "Verification of hot-spot in complex composite structures using detailed FEA"
Molker, H., Gutkin, R. & Asp, L. E.
ECCM18 - 18th European Conference on Composite Materials, Athens, Greece, 24th-28th June 2018.

Molker proposed the set-up of the framework and performed the implementation. Molker wrote the paper with assistance from Gutkin and Asp.

Contents

1 Introduction

The automotive industry faces an outstanding challenge to reduce the environmental impact due to car transportation. Car transportation is responsible for 17.5% of the greenhouse gas emissions in Sweden [1] and 12% of the total CO_2-emissions in Europe. With current legislation within the European Union [2], shown in Figure 1, an upper limit of 70 g CO_2 / km is in place for 2025 compared to 130 g CO_2 / km in 2015 [2]. During the UN climate summit in 2018, future reductions for EU by 37.5% from 2021 levels to 2030 were agreed upon [3]. In order to reach the vision of a climate neutral Sweden by 2050, the emissions from new cars would need to be reduced to 0 g CO_2 / km already by 2030 [4].

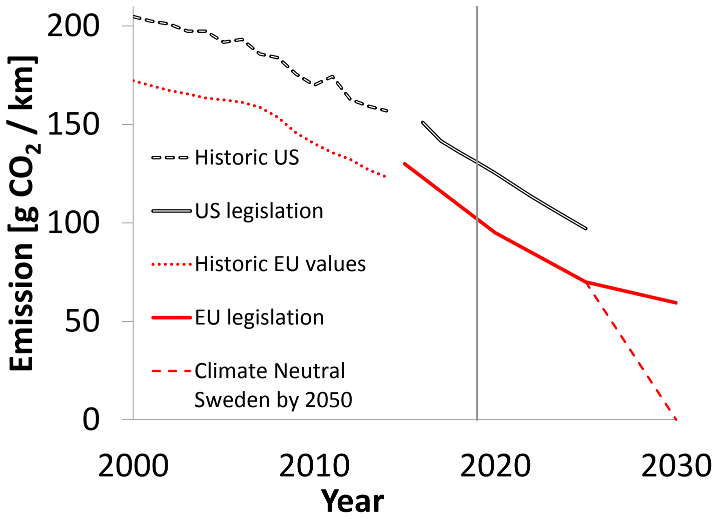


Figure 1. Historic CO_2-emission from passenger cars and current US and EU legislation [2], the newly agreed reductions in EU to 2030 [3] and the required change to reach a climate neutral Sweden concerning greenhouse gas emissions by 2050 [4].

The current trend in automotive industry is to introduce electric vehicles. Even though this significantly reduces the CO_2-emissions, climate neutral electricity is today a limited resource [5], contributing to less than half of the electricity produced in Europe. The need for energy efficient solutions will therefore not only be needed for traditional Internal Combustion Engine (ICE) cars but also Battery Electric Vehicles (BEV).

1.1 Effect of mass

A reduction of the weight by 10% of a car reduces the fuel consumption by approximately 7% [6]. For BEVs this can either allow for a reduced battery package or an increased range. Cars made from Carbon Fibre Reinforced Polymer (CFRP) materials are considered to be 50% lighter compared to steel alternatives and 30% lighter compared to aluminium alternatives with similar performance [7]. Hence, composites are an outstanding alternative and needed to reach the anticipated structural mass savings required by 2025 [8]. Reduction of the structural mass can also result in secondary savings, e.g. smaller powertrains, smaller brakes, etc., without decreased performance.

Over the last half century, the weight of cars has steadily increased. Looking at cars from the C/D and D/E classes [9] for ICE powered vehicles, there is an increase of 13 kg per year from the 1950s to today. This can be seen in Figure 2 where the kerb weights are shown for six European car brands and their models in the C/D and D/E classes. BEVs have entered the market in larger numbers over the last five years. The kerb weights of BEVs from nine different brands are also shown in Figure 2. As these car models in most cases still are the first generation, it is not possible to see any trends in the weight development. However, it is clear that the weight of these cars is in the same range as current ICE vehicles. It is important to note that the BEVs shown are from both smaller and larger cars than found in the C to E class, explaining the large span found in Figure 2.

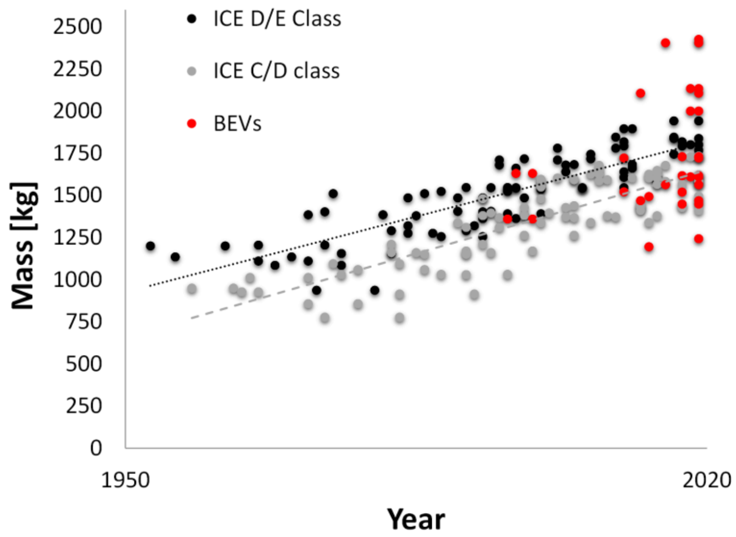


Figure 2. Evolution of kerb weight for cars over the last 50 years. The average weight is shown for ICE cars. Black dots are D/E class cars, grey dots are C/D class cars. The car models are from Audi, BMW, Mercedes, Volkswagen, Volvo and Saab. The red dots are BEVs. Source: Wikipedia, Car model and Kerb weight.

As the increase in mass is attributed to increased safety features and increased user experience expectations, the only way to decrease the weight is to actually reduce the weight of existing components. For both ICE vehicles and BEVs, decreasing the weight will lead to more energy efficient cars. For ICE this is directly related to a decrease in CO_2 emissions. For BEVs, this can either be utilized to increase the range, to overcome range anxiety, or to downsize the battery packs while keeping the performance of the car [10].

Current car structures are predominantly built from two metals, steel and aluminium, in different forms and grades. As an example, the material mix for the 2019 Volvo V60 can be seen in Figure 3. Even though there are differences between the OEMs, there is still a similarity in the choices of the materials used in different parts.

Looking at the specific properties for metals, e.g. steel, aluminium and magnesium, and some Fibre Reinforced Polymers (FRP) one can see in Figure 4 that the possibility to lightweight with these materials is limited [11,12]. The specific strength can be somewhat tailored for metals while the specific stiffness is more or less the same. However, for composite materials, not only the specific properties are superior, but the properties can be tailored to a much higher degree.

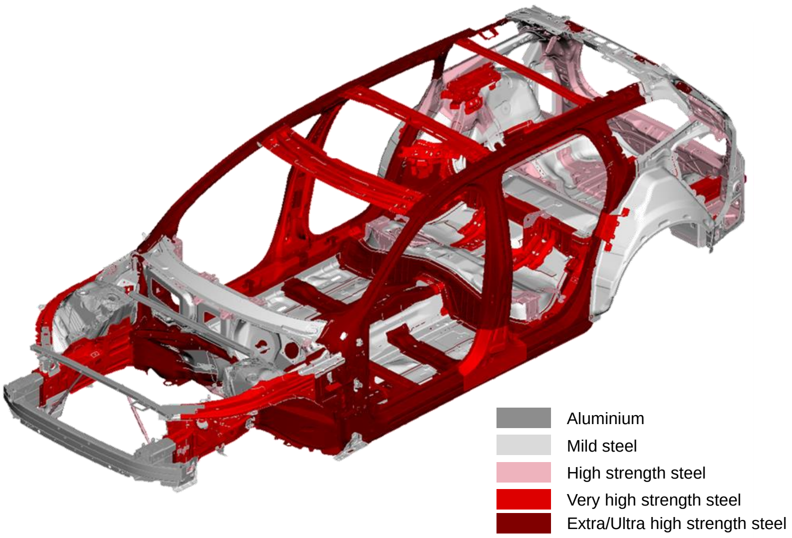


Figure 3. Material selection in the Volvo V60 (2019) body-in-white structure. Courtesy by Volvo Cars.

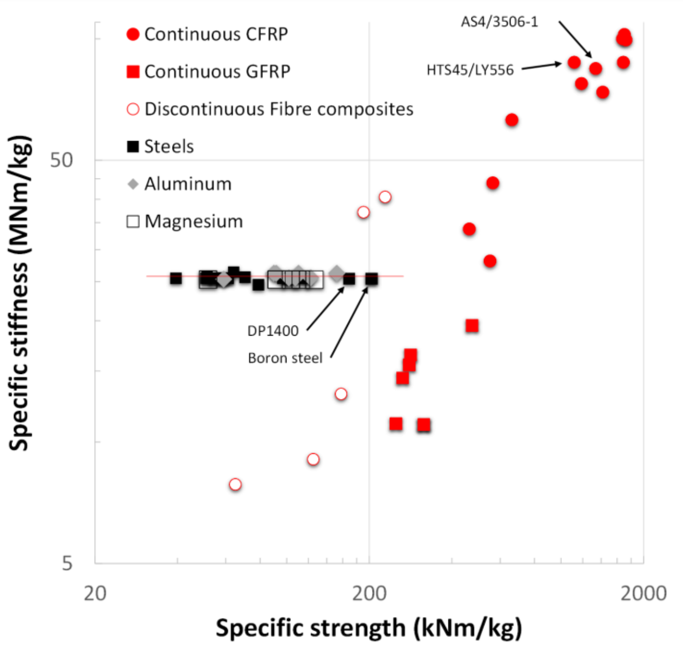


Figure 4. Chart of the specific stiffness and strength for common engineering metals and FRP materials [11,12]*. Note the almost constant specific stiffness for metals.*

1.2 Composite materials for structural applications in the automotive industry

Composite materials, as seen in Figure 4, have outstanding specific properties. But what are the engineering challenges that must be overcome to see these outstanding materials as candidates in structural applications within the automotive industry?

Composite materials have been used within the automotive industry for a long time in non-structural or semi-structural parts, e.g. tailgates. The materials used in such components can be divided into two categories; Short Fibre Reinforced Polymers (SFRP) and Discontinuous Fibre Reinforced Polymers (DFRP). The SFRP are made from polymers that are filled to a low extent with short fibres, often glass fibres. Such components are not primarily structural components and can be analysed with the same tools as other filled polymers. These materials are considered to be isotropic, see Figure 5 (a). The DFRP are found in semi-structural components in cars, e.g. the tailgate of the Volvo V70 and the Toyota Prius [13,14]. These materials are transversely isotropic with the same properties in the plane of the “sheet” and other properties in the out-of-plane direction, see Figure 5 (b). These structures are often analysed in the same way as both isotropic short fibre composites and sheet metals, assuming that the out-of-plane direction can be neglected.

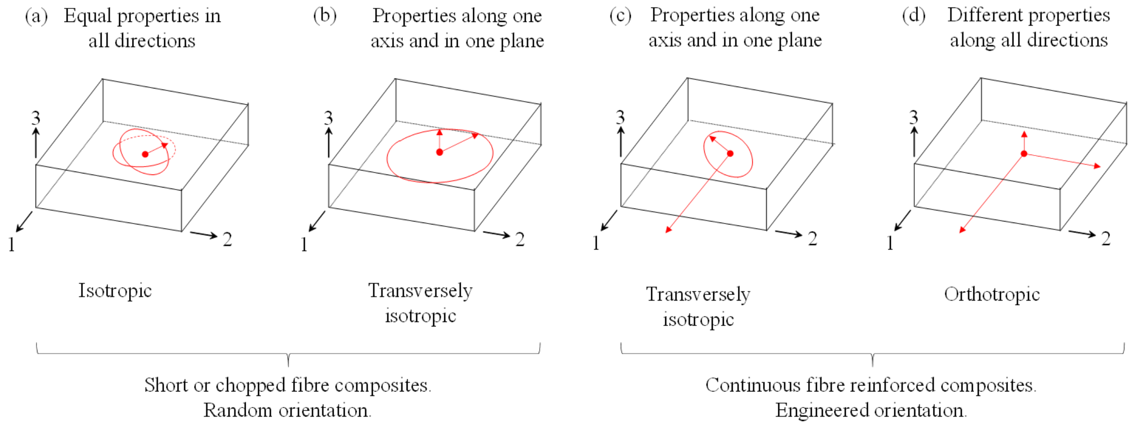


Figure 5. Materials with different properties in different directions. (a) Isotropic material with properties that are equal in all directions. (b) Transversely isotropic material with properties defined along one axis and one plane, in this case a layered material, e.g. a Sheet Moulding Compound (SMC) composite. (c) Transversely isotropic material with properties defined along one axis and one plane, in this case a tape-based laminate. (d) Orthotropic material with properties defined along three principal axes.

To get the very best properties from FRPs and to be able to tailor them, continuous fibre composites are used in a layered structure. This is the common type of FRP systems used for structural applications, e.g. in aerospace applications, car racing etc. The laminates are made of several laminae stacked in different directions to best suit the design. Each lamina is made from tapes with pre-impregnated fibres and is transversely isotropic with one set of properties in the fibre direction and another in the transverse plane, see Figure 5 (c). These materials are then analysed using Classic Laminate Theory (CLT) in order to get homogenised properties. Similar laminates can be built up using fibre bundles that are woven into textiles. The advantage is that more manufacturing techniques are available and that more material can be applied at the same time compared to tape-based systems. The disadvantage is that the fibres become crimped due to the weave, see Figure 6 (b), which decreases the performance, particularly under compression.

To reduce the effect of the waviness of the textile, instead of weaving warp and weft yarns one can stitch them together with much thinner binding yarns. This will significantly reduce the crimp of the material. Such textiles are called Non Crimp-Fabrics (NCF). The crimp is defined [15] as:

$$C = \frac{l_y - l_f}{l_f}, \tag{1}$$

where C is the crimp, l_y is the length of the yarn in the fabric, and l_f is the length of the fabric.

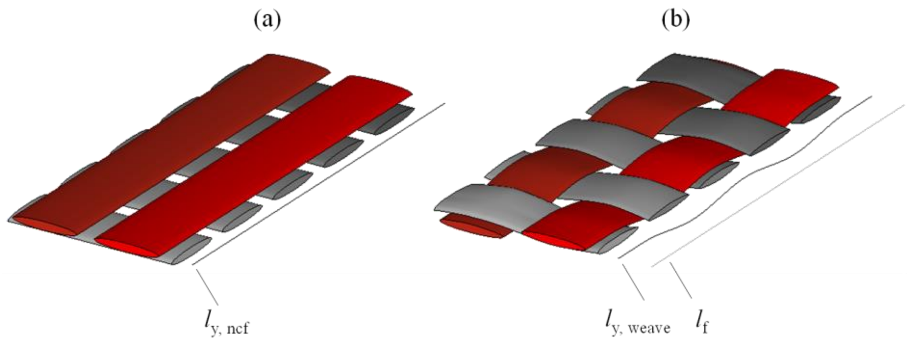


Figure 6. Schematic image of the fibre architecture of (a) a UD NCF textile and (b) a weaved textile.

Structural components made from CFRP were first found in the automotive industry in 1981 when McLaren designed a CFRP monocoque for the MP4/1 Formula One car [16]. This rapidly became the standard within formula 1 and other car racing series. Introduction into small series production of cars was done, once again by McLaren, in the F1 in 1993 to 1998 [16]. This shows the outstanding possibilities, but also implies that there are some outstanding challenges, as the use of composite materials has not yet spread to primary structures in the automotive industry.

CFRP can be found in high performance cars and brands more or less ever since the introduction in the McLaren F1. For every new generation, the content of CFRP composites has increased. In these cars, most of the structure is made with a CFRP monocoque as shown in Figure 7 (a) for the Porsche 918. In a similar way, the BMW i3, launched in 2013, uses a CFRP life module shown in Figure 7 (b). The BMW i3 and i8, where a similar structure is used [17], are still low volume cars, produced in about 30’000 units annually of the BMW i3 and 5’000 units annually of the BMW i8. In larger series, structural components can be found in the latest BMW 7-series called carbon core [18] and in the new Audi A8 [19].

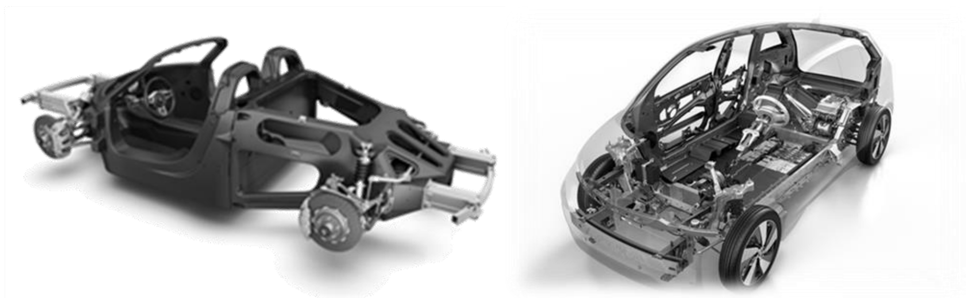


Figure 7. (a) Body structure of Porsche 918 with a CFRP main structure and metal front and rear structures [20]. Right: BMW i3 with front and rear structures in metal and the passenger cell in CFRP [17].

However, although the CFRP content is increasing in automotive structural parts, it is not used in the primary crash structure of a car. To absorb the energy from a crash, metal structures are used in the front and rear. This is related to the difficult topic of predicting progressive failure and crash behaviour in structures made from CFRP [21].

For highly loaded automotive structures where composites are used, continuous fibre systems are the dominant choice, with the exception of Lamborghini that uses a developed version of Sheet Moulding Compounds (SMCs) in their cars [22].

In aerospace, the most common composite material systems are tape-based and pre-impregnated, that are preformed and cured in an autoclave. These systems give the best performance but are associated with long production cycles times and high cost. For the automotive industry, where the balance between performance and cost pivots more towards cost, dry textile preforms, such as weave and NCFs that are impregnated during manufacturing, e.g. Resin Transfer Moulding (RTM), are more advantageous. The whole body structure of the BMW i3 is made from NCF reinforced composite materials that are manufactured with RTM [23]. One drawback with these systems is that they are less explored when it comes to the understanding of their failure mechanisms, and numerical methods to analyse the materials and their failure modes.

1.3 Challenges for composite materials in structural applications

The automotive industry is focused on cost and therefore introduction of new materials, although with superior properties, needs to be cost effective. As carbon fibre composites are more expensive compared to materials traditionally used in the automotive industry they need to be used effectively. Benefits in the long term of introducing composites are shown from an economic point of view in EUR/km per kg saved weight by Redelbach et al. [10] and from a life cycle perspective by Gibson [24].

Successful introduction of high performance composite structures in automotive industry also requires new ways of designing structures and components. This to avoid that composite materials are used as “black-metal” but instead taking full advantage of their superior properties. A guideline for designing with composites in the automotive industry is proposed by Mårtensson [25].

Although there are incentives from cost and environmental perspectives to introduce high performance composite materials in structural parts, technical difficulties in doing so still exist. One major roadblock for higher utilisation of composite materials and their superior properties in more industries than aerospace is the lack of efficient and accurate analysis methods that do not rely on extensive test campaigns to demonstrate a safe design [26].

2 Aims and scope of this thesis

Development processes within the automotive industry heavily rely on numerical methods and tools to be able to deliver within short project times. The tools and methods available from the aerospace industry, where CFRP constitutes about half of the structural weight, are developed for tape-based UD pre-impregnated material systems. Moreover, the building block approach used in aerospace requires extensive physical testing, which is both time consuming and costly.

For automotive application of composites, efficient, yet robust, numerical tools must be developed. They need to handle a multitude of material systems, not only tape-based systems but also woven fabrics and NCFs. As materials develop rapidly, the methods should also be general, to cover other similar systems that may have different types of constituents, e.g. thermoplastic matrices instead of thermosets.

From this scope, two main research questions are formulated:

- RQ.1. What are the failure modes in orthotropic Non-Crimp Fabric (NCF) composite materials and how should they be predicted?

- RQ.2. How should a framework for efficient and reliable strength analysis of automotive composite structures be constructed?

The first question covers the understanding of how failure occurs in composite materials with orthotropic properties, with the focus on NCF reinforced composite material systems. With the knowledge of how failure occurs, this can be modelled and predicted using Finite Element Models (FEM).

The second question covers an approach on how complex materials, with failure mechanisms occurring at the scale of the ply thickness, i.e. tenths of a mm, can be modelled in full car models. Typically, such FEM today are run over night to keep up with the pace in the product development process. Traditional models use element sizes of a couple of mm, and modelling with more refined meshes at one order of magnitude below would simply yield too large models.

2.1 Methodology

The research is based on deductive approaches [27]. Predicting failure in composite materials have evolved over time with the first failure theories presented in the 1950s', e.g. Azzi and Tsai [28]. Over time, these theories have been tested against more and more experimental data, and when proven not to be accurate enough, new theories have been proposed [26].

The first research question is based on the background of literature studies that reveals the orthotropic nature of NCF reinforced composite materials. To address failure in NCF composite materials, the research is conducted based on data from the literature to understand the material behaviour. Based on these findings, numerical simulations are performed to further increase the knowledge of these materials, and a hypothesis regarding failure mechanisms is formulated.

Numerical simulations are commonly used to understand how composite materials behave at the micro- and mesoscales [29]. These models can be used to set studies up in a controlled way where only the desired parameters are changed. This is something which can be very difficult in actual experiments as the process of going from separate constituents to a manufactured and properly set-up physical test, where the desired responses can be retrieved, can be very difficult and time consuming.

With the knowledge gained from literature studies and numerical simulations, a physical experiment is designed and performed such that the proposed hypotheses and models can be evaluated against actual data.

For the second research question, the foundation is based on literature studies to understand what prerequisites are needed to actually address potential failure modes. With this knowledge, scrutinise what analysis methods are available to accomplish this. The final part is to see how this can be included in an environment that is suitable for the automotive industry. The proposed set of tools in a chain is then tested on structural components to validate its applicability.

2.2 Limitations

This work will only focus on durability related failure of composite structures. This implies that first ply failure [30] is of interest, while progressive damage is not. The composite materials that have been studied are layered materials with transversely isotropic or orthotropic properties, see Figure 5 (c and d).

The proposed approaches and methods should, as far as possible, be easy to implement in software environments commonly used in industry.

3 Failure of orthotropic NCF composite material systems

For the automotive industry, there are many aspects to keep in mind when selecting materials, and even more so for composite material systems. Key aspects for composite materials are the cost and the production cycle times while maintaining the outstanding properties of continuous fibre systems. Non-Crimp Fabric composite systems have properties close to those of UD composite systems [31,32]. As they can be manufactured with the resin transfer moulding (RTM) process, the cost is not as high as for pre-impregnated systems. NCF composite materials can also be manufactured as mats with predefined material orientation, which makes it possible to apply a large amount of reinforcement material in a short period of time [33].

NCF composite materials are more complex in their structure and developed in more recent times compared to UD composites systems. NCF composite materials have been found to be orthotropic in their nature [12,34]. Both the elastic properties, as well as the strength of NCF composite materials are orthotropic.

Today's State of the Art (SotA) sets of failure initiation criteria are today mainly developed for UD composite materials and with the failure modes found in these types of materials. Failure in UD composite materials have been studied in three successive global studies, World Wide Failure Exercises [35–37], to understand how well failure of these materials can be predicted. No such effort has been undertaken to understand failure in textile systems. For NCF composite materials, two different failure initiation criteria can be found in the literature [38,39]. Both address the orthotropic nature, but neither relate to any studies of the failure modes associated with NCF composite materials.

In this work, failure in UD NCF reinforced composite materials is studied. Before going into details of failure in NCF composite materials, the basic failure modes for UD composite materials are discussed in section 3.1. These failure modes are found within fibre bundles in NCF composite materials and are therefore of relevance.

3.1 Failure in UD composite materials

UD composite materials are considered to be transversely isotropic both in terms of elastic and strength properties. Failure is predicted on the ply level in the composite laminate and the properties used are on lamina level.

SotA failure initiation criteria are physically based, which means that they capture the failure mechanisms and address specific failure modes. UD composite materials show three main failure modes; fibre tensile failure, matrix related failure, and fibre kinking (compression in the fibre direction). These failure modes are evaluated in all top ranked failure theories by Cuntze [40], Pinho et al. [41], and Carrere [42] in the World Wide Failure Exercise II [43].

The different failure modes are described in the following paragraphs, using the set of failure initiation criteria found in LaRC05 [41].

Fibre tensile failure, shown in Figure 8, is governed by the strength of the fibres and the stress in the fibre direction, σ_{11}. The Failure Index (FI) for fibre tensile failure is evaluated according to the criterion:

$$FI_{\mathrm{FT}} = \frac{\langle \sigma_{11} \rangle_+}{X_{\mathrm{T}}} = 1, \tag{2}$$

where X_{T} is the strength measured in the 1-direction.

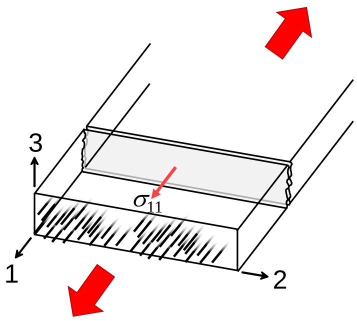


Figure 8. Illustration of tensile fibre failure for a UD lamina in a composite material under pure σ_{11} loading.

Matrix related failure in the transverse direction, illustrated in Figure 9 (a) for tensile loading and (b) for compressive loading, is governed by the properties of the matrix material. Many common matrix materials, e.g. epoxy, show brittle failure and fail by shear under compression [44]. For matrix tensile failure, illustrated in Figure 9 (a), a quadratic relationship between the normal stress and shear stresses have been found to capture failure initiation [44]. The tractions on a potential fracture plane, τ_{T}, τ_{L} and σ_{N} are compared to the allowable S_T^{is}, S_L^{is} and Y_T^{is} and evaluated as for matrix tension $FI_{\mathrm{M,T}}$:

$$FI_{\mathrm{M,T}} = \left(\frac{\tau_{\mathrm{T}}}{S_{\mathrm{T}}^{\mathrm{is}}}\right)^2 + \left(\frac{\tau_{\mathrm{L}}}{S_{\mathrm{L}}^{\mathrm{is}}}\right)^2 + \left(\frac{\sigma_{\mathrm{N}}}{Y_{\mathrm{T}}^{\mathrm{is}}}\right)^2 = 1, \tag{3}$$

where the superscript "is" denotes the in-situ strength which takes the thickness and location inside a laminate into account [41].

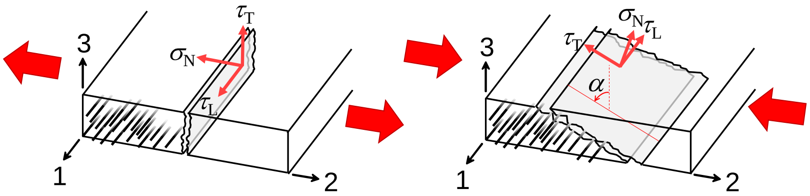


Figure 9. Illustration of a) tensile, under pure σ_{22} loading, and b) compressive, under pure $-\sigma_{22}$ loading, matrix failure for a UD lamina in a composite material.

Under compression, the matrix material fails at an inclined fracture plane as illustrated in Figure 9 (b), suggesting that the failure is driven by shear forces. For this reason, a modified Mohr-Columb criterion is used in several failure criteria, e.g. LaRC05 [41] and Puck and Schürmann [45]. Under pure compression, the fracture plane tends to be inclined more than 45° which implies that friction on microcracks increases the allowable shear stress [44]. The friction stress from the microcracks is calculated from the normal stress, σ_N, and a friction coefficient in the transverse, η_T, and longitudinal directions, η_L. The criterion for matrix compression, $FI_{M,C}$, is evaluated according to:

$$FI_{M,C} = \left(\frac{\tau_T}{S_T^{is} - \eta_T \sigma_N}\right)^2 + \left(\frac{\tau_L}{S_L^{is} - \eta_L \sigma_N}\right)^2 = 1. \tag{4}$$

Both for tension and compression, the *FI* needs to be evaluated for any potential fracture plane by varying the angle α. This can be done at either a fixed number of potential planes [44], e.g. every 15° or by an optimisation algorithm [46]. The fracture plane with the highest *FI* gives the critical fracture plane.

To simplify the matrix related failure assessment, Equations (3) and (4) can be combined to one criterion for matrix related failure FI_M as found in LaRC05 [41]:

$$FI_M = \left(\frac{\tau_T}{S_T^{is} - \eta_T \sigma_N}\right)^2 + \left(\frac{\tau_L}{S_L^{is} - \eta_T \sigma_N}\right)^2 + \left(\frac{\langle \sigma_N \rangle_+}{Y_T^{is}}\right)^2 = 1, \tag{5}$$

where $\langle \quad \rangle_+$ denotes the McCauley bracket. This only affects the tensile failure, where spurious friction appears. However, as tensile failure is mainly governed by the transverse tensile strength Y_T, this has a minor effect. The allowable shear is often twice in magnitude compared to the transverse tensile strength.

Fibre compressive failure exhibits two different failure modes, *fibre kinking*, illustrated in Figure 10 (a) and *fibre splitting*, illustrated in Figure 10 (b). These are in fact matrix controlled failure modes. Fibre kinking is initiated due to local misalignments of fibres causing shear stresses that increase during rotation of the fibres [44]. Under compression, the misalignment increases, and at some point causes the matrix failure in a transformed coordinate frame, denoted with superscript m. The criterion for fibre kinking FI_{KINK} is evaluated in LaRC05 [41] as:

$$FI_{KINK} = \left(\frac{\tau_{23}^m}{S_T^{is} - \eta_T \sigma_{22}^m}\right)^2 + \left(\frac{\tau_{12}^m}{S_L^{is} - \eta_L \sigma_{22}^m}\right)^2 + \left(\frac{\langle \sigma_{22}^m \rangle_+}{Y_T^{is}}\right)^2 = 1. \tag{6}$$

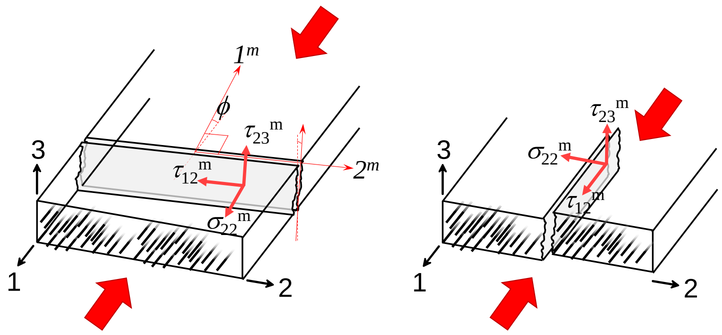


Figure 10. Illustration of compressive fibre failure for a UD lamina in a composite material, (a) fibre kinking and (b) fibre splitting.

The two failure modes are predicted with the same criterion, given in Equation 6. The distinction between fibre kinking and splitting according to Equation 7 is empirical in

LarRC05. Fibre kinking and fibre splitting are distinguished with the magnitude of the fibre direction stress according to:

$$\begin{aligned} &\text{Kinking if } \sigma_{11} < {}^{-X_\mathrm{C}}/_{2} \\ &\text{Splitting if } \sigma_{11} \geq {}^{-X_\mathrm{C}}/_{2}, \end{aligned} \tag{7}$$

where σ_{11} is the stress in the fibre direction, and X_C is the measured compressive strength.

3.2 Failure in NCF composite materials.

Textile systems such as NCF have a different architecture compared to UD tapes, even in the form of UD NCFs, and textile weaves. The stitching yarn that binds one or more layers introduces non-uniformities in the final material. Their severity can differ depending on the manufacturing. This includes both the choice of materials for the stitching yarn and how the architecture of the stitching yarn is distributed throughout a laminate [47].

The stitching yarn, the tow structure and the shape of the bundles will also introduce stress concentrations when loaded in the transverse direction. Moreover, compared to full 3D composite materials that have a fibre architecture in all directions throughout the thickness, NCF composite materials are made of several mats stacked to the desired layup. This means that there will not be fibres that can carry load through the thickness and at interfaces between mats there will be a higher concentration of stitching yarns.

Failures originating from transverse loading are found to occur in two different modes for NCF composite materials [34]. The first failure mode occurs as matrix cracks inside the fibre bundles, called intrabundle matrix failure, see Figure 11 (a). This is the same failure mode that occurs in UD tape-based composites, see Figure 9 (a). The other failure mode occurs between the fibre bundles in the out-of-plane direction, see Figure 11 (b). This has been observed by Olsson [34] and Edgren et al. [48].

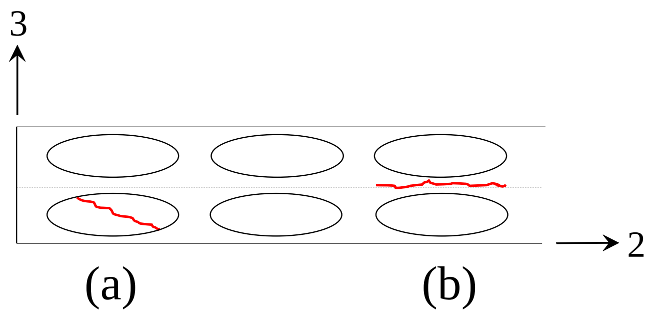


Figure 11. Matrix failure modes associated with transverse matrix failure. (a) failure inside a fibre bundle, called Intrabundle matrix failure. (b) failure in-between plies of NCF mats, called Interbundle matrix failure.

NCF reinforced composite material systems have been found to be orthotropic in experimental studies by Olsson [34] and Bru [12]. The out-of-plane strength in tension is found to be considerably lower compared to the transverse in-plane tensile strength. This difference is coupled to the different failure modes found in NCF reinforced composite materials.

The out-of-plane strength is studied in **Paper I** and found to be associated with stress concentrations related to small perturbations of the cross section geometry of a fibre bundle, see Figure 12, in **Paper I** under out-of-plane loading. Numerical simulations have been carried out to understand how bundle shapes, temperature change during manufacturing and material properties can affect the strength of an NCF composite material.

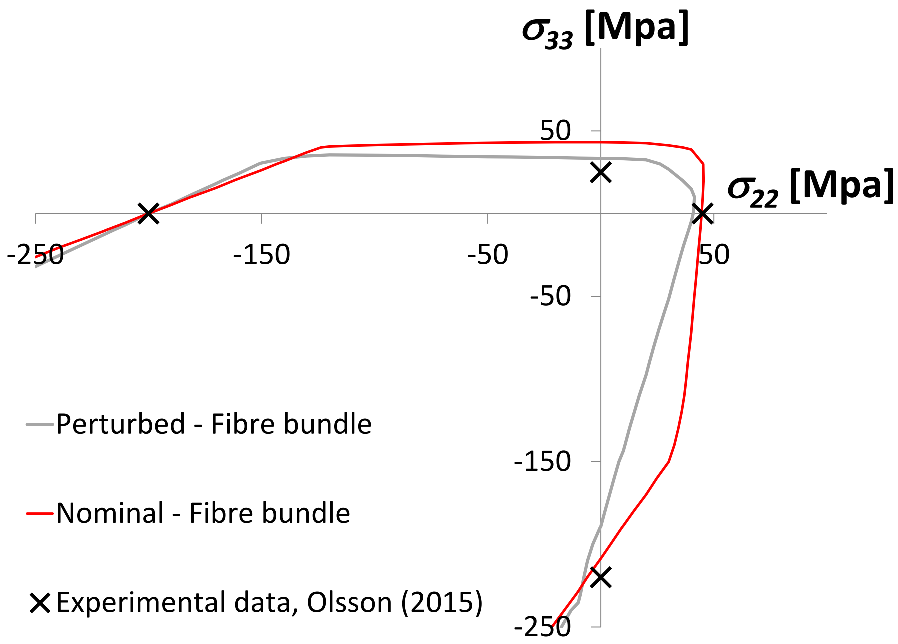


Figure 12. Fibre bundle failure for different bundle shapes studied in Paper I.

Few sets of failure criteria exist for composite materials with orthotropic properties, at least in relation to the vast amount of failure criteria for UD tape-base composites. One set of criteria, originating from the criteria proposed by Puck and Schürmann [45], is proposed by Juhasz et al. [38]. This set of criteria acknowledge the introduction of fibres in the out-of-plane direction and associates this to the out-of-plane strength. However, this failure criterion is based on an increased strength in the out-of-plane direction with fibre failure as the failure mechanism. Failure of the stitching yarns in NCF composite materials as the initiation at out-of-plane failure has not been observed. This set of criteria also needs fitting of the parameters used, as it does not use properties directly measurable in experiments, which makes it more difficult to employ.

Another criterion proposed by Rolfes et al. [39] is based on the strength values for tension and compression in each principal direction together with the shear values. With these nine properties, an invariant-based criterion is formulated which gives an orthotropic failure surface. However, the criterion does not have interactions between the different basic failure strengths more than that it should be a mathematical fit, and it is not necessarily or shown to be physical.

3.3 Proposed set of failure criteria for failure initiation in NCF composite materials

Based on the knowledge of the failure modes found in NCF composite materials a physically motivated set of failure criteria is proposed on the lamina level. The set of criteria is based on the LaRC05 [41] failure criteria for UD composites. To address the failure that occurs under out-of-plane loading, an additional failure mode is added for transverse matrix failure in **Paper I**.

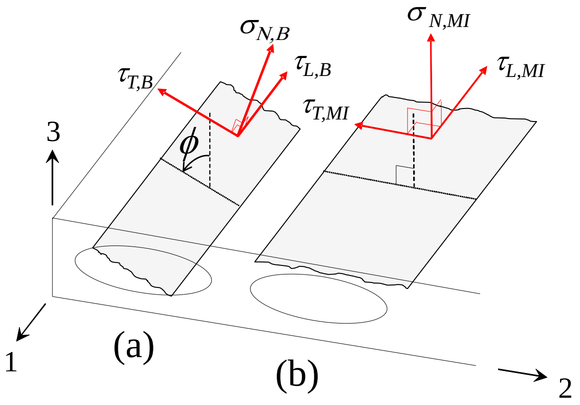


Figure 13. Matrix failure modes associated with transverse matrix failure. (a) failure inside a fibre bundle, called intrabundle matrix failure. (b) failure in between plies of NCF mats, called interbundle matrix failure.

For transverse failure that occurs within the fibre bundle, (B), the failure criterion in LaRC05 [41] is used,

$$FI_{\mathrm{M,B}} = \left(\frac{\tau_{\mathrm{T,B}}}{S_{\mathrm{T}} - \eta_{\mathrm{T}}\sigma_{\mathrm{N}}}\right)^2 + \left(\frac{\tau_{\mathrm{L,B}}}{S_{\mathrm{L}} - \eta_{\mathrm{L}}\sigma_{\mathrm{N}}}\right)^2 + \left(\frac{\langle\sigma_{\mathrm{N,B}}\rangle_+}{Y_{\mathrm{T}}}\right)^2 = 1. \tag{8}$$

For transverse failure in the out-of-plane direction that occurs within the matrix, (MI), the following criterion is proposed

$$FI_{\mathrm{M,MI}} = \left(\frac{\tau_{\mathrm{T,MI}}}{S_{\mathrm{T}} - \eta_{\mathrm{T}}\sigma_{\mathrm{N}}}\right)^2 + \left(\frac{\tau_{\mathrm{L,MI}}}{S_{\mathrm{L}} - \eta_{\mathrm{L}}\sigma_{\mathrm{N}}}\right)^2 + \left(\frac{\langle\sigma_{\mathrm{N,MI}}\rangle_+}{Z_{\mathrm{T}}}\right)^2 = 1, \text{ if } \sigma_{\mathrm{N}} > 0. \tag{9}$$

This is evaluated under pure tensile loading for a fracture plane $\alpha = 90°$.

The transverse matrix failure index is then defined as the maximum of $FI_{\mathrm{M,MI}}$ and $FI_{\mathrm{M,B}}$ for all angles

$$FI_{\mathrm{M}} = \max\left(FI_{\mathrm{M,MI}}, FI_{\mathrm{M,B}}\right). \tag{10}$$

Failure envelope predictions in the σ_{22}-σ_{33} plane with this set of failure initiation criteria are shown in Figure 14 for two different material systems.

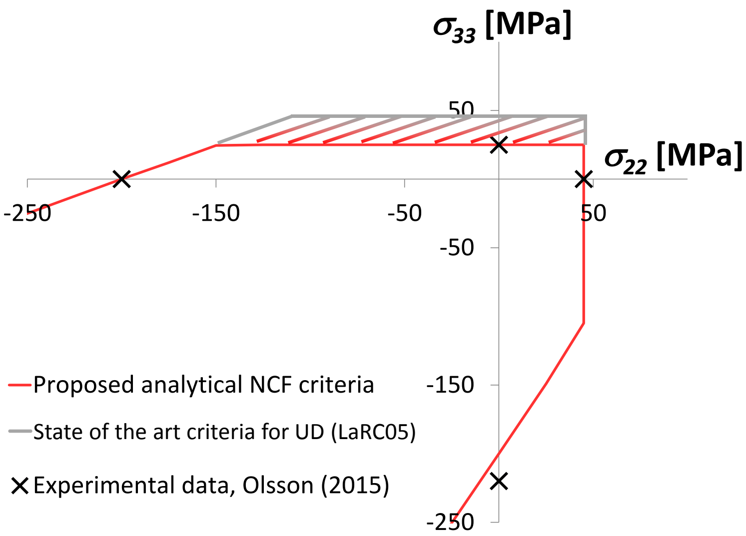


Figure 14. Failure envelope predictions with the proposed failure criteria in the σ_{22}-σ_{33} plane. [34].

3.4 Implementation and verification of proposed set of failure initiation criteria

The proposed set of failure initiation criteria for NCF composite materials from **Paper I** is implemented in the commercial FE solver Abaqus [49] in **Paper II**. It is implemented as a user variable, UVARM [49]. In the implementation, all possible failure modes are predicted for each material point in the model. The output is the failure index, for the most critical fracture plane, with the most critical failure mode under the current stress state.

The implementation is intended for models using solid elements with one element over each ply thickness. This means that it can be used on test specimen models. With larger models, the computational cost would be too large.

To verify the failure criteria and the implementation, experimental tests have been performed in **Paper II**. Corrugated specimens, as shown in Figure 15, with two different layups, $[90]_{16}$ and $[90/0]_{8S}$ of HTS45/LT556 material [12] are tested. The specimens are loaded with a prescribed displacement along the top of the specimen while the lower part is placed on plates on rollers to reduce friction. This set-up will open up the specimen and create out-of-plane stresses.

From the experimental tests, it is found that the failure for both layups occurs at the location with the highest out-of-plane stress. This occurs at an angle of about 25° degrees from the top, due to the compressive stresses at the top, and about halfway through the specimen.

Figure 15. Corrugated specimen sued for out-of-plane strength predictions with proposed failure initiation criteria. The specimen is approximately 40 x 20 x 20 mm in size and 3 mm thick.

Predictions made with the proposed failure initiation criteria are compared to the experiments and the SotA failure initiation criteria for UD composite materials LaRC05 [41]. From these comparisons, shown in Figure 16, it can be concluded that the proposed criteria capture the correct failure mode for both layups. This is not the case for LaRC05, where the lower out-of-plane strength compared to the in-plane strength is neglected since transverse isotropy is assumed.

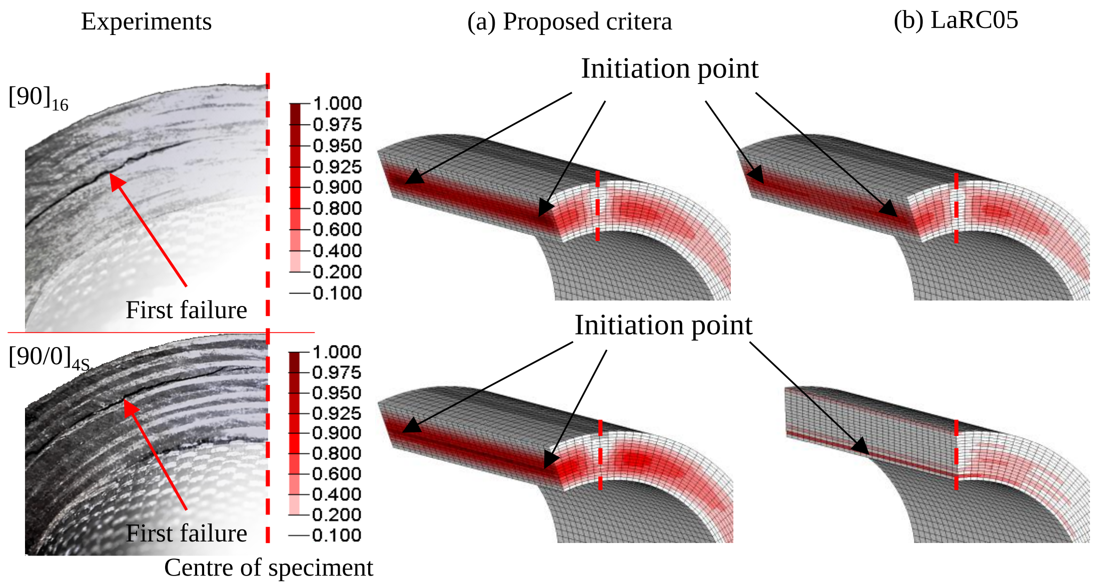


Figure 16. Left: Location of failure initiation from the experiments. Right: Initiation points predicted with the (a) proposed set of criteria and with (b) LaRC05.

Further scrutinising the results of **Paper II**, it is evident that the out-of-plane strength is a property that is difficult to measure. Strength values should be obtained from specimens that are similar to the laminates that are to be analysed [50,51]. This is even more true for NCF composite materials since more defects are introduced by the stitching yarn. Comparing the test specimens used by Bru et al. [12] and the specimens used in **Paper II**, the weakest link theory proposed by Wisnom [52] can be used to relate the strength with the size of the highly loaded volume in each test set-up.

4 Analysis methodology

Product development, e.g. development of a new car model, follows a process to ensure that the design fulfils all requirements. The scope of the Product Development System (PDS) covers all stages from market analysis to end-of-production [53]. The detailed design phase of the product, the execution or concept/engineering phase, has only a short limited time in order to not miss the market opportunity. Therefore, during this part, milestones and gates need to be passed to ensure that the design complies with all requirements. It is within this phase that methods and means are needed to ensure that the product fulfils strength and durability requirements. This will from here on be referred to as “analysis methodology”, with focus on durability aspects.

Future trends within the automotive industry are that the time-to-market will be further reduced as the industry transforms from supplying a product - a car - to more of a service provider [54]. Also, the lifetime of platforms will continue to decrease, on average the platform lifetime (either substantial revision or retirement) has decreased by a year per decade over the last 40 years [54].s

4.1 Analysis of traditional materials within the automotive industry

The design of traditional materials, e.g. metals and polymers, are from a durability point of view driven by Computer Aided Engineering (CAE) methods, e.g. Finite Elements Methods (FEM), and Multi Body Simulations (MBS). This simply is a consequence of the fact that physical testing within each design is not feasible and that the reliability and accuracy obtained from these methods are good enough.

The current state has not been achieved overnight but has been an evolutionary process over time. Along this journey, the need for physical testing of large assemblies and full scale tests has reduced and been replaced by CAE methods as the cycle times between milestones in the PDS have gradually shortened.

Today, durability analyses for complete vehicles are performed with FEM models of full-scale cars or models with very large subsystems, e.g. Body In White (BIW), full door structures, front ends, etc. This results in large models where shell element formulations, based on Mindlin-Reissner [55] or Kirchhoff-Love [56] theory, are used, giving efficient simulations and balancing solution time and accuracy. One important assumption here is that only the in-plane results are of concern, as the out-of-plane stress and strain components are neglected. Moreover, the use of complete, or at least large assemblies, simplifies the process of finding the correct loading and boundary conditions as these can be directly applied to the models like they appear in reality.

4.2 Design of composite structures within the aerospace industry

In the aerospace industry, the building-block approach [57] is used for the design and analyses of composite structures. The approach is illustrated in Figure 17. It is a bottom-up process where knowledge from each level is transferred to the next level, all the way from coupons to full structure. However, as the models do not necessarily capture failure at other levels, developed material models do not necessarily work at another level. The advantage is that the models at each individual level can be simplified. But it is hard to find predictive models that work at multiple scales.

Even if the modelling can be kept simple, all loads need to be transferred from the full scale level down through the pyramid. This is done with load distribution models, where loads are distributed from a coarse global model down to smaller areas. These load models are often complicated to create, as the simplicity in the modelling technique requires numerous different effects to be taken into account. The models are in most cases linear and cannot take nonlinear effects into account.

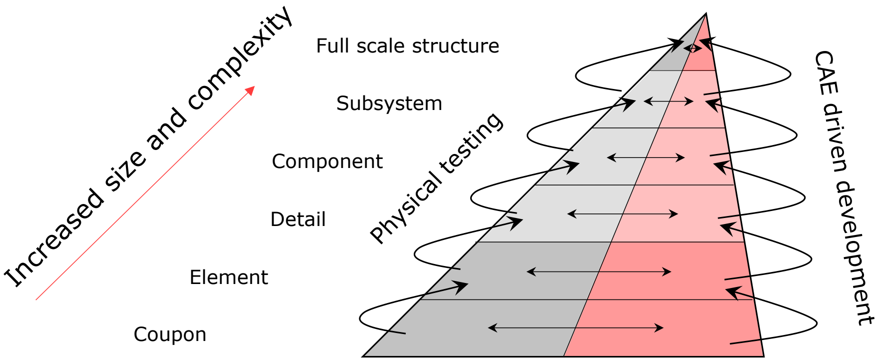


Figure 17. Building-block approach and how it is used within aerospace [57]. *Modelling and physical testing are performed at each level. Numerical models only need to predict failure that occurs in the corresponding tests and does not need to be predictive for other levels.*

As calculation capacity has increased over the last decade, more complex numerical models can be used, which reduces the need for simplified models. In aerospace industry, this is done in the Wishbone framework [58], illustrated in Figure 18. The two clavicles of the furcular in the process are made up from a structural screening part and a method development part. In the screening, more advanced models of full scale structures are built, taking non-linear effects into account. These are then broken down to more detailed models using sub-modelling to achieve the correct load distribution. In the method development, detailed modelling techniques are established from coupon level up to structural features. Both parts are validated with physical test data. At the fusion of the wishbone, verification of structural elements is done using models with the same complexity from both clavicles.

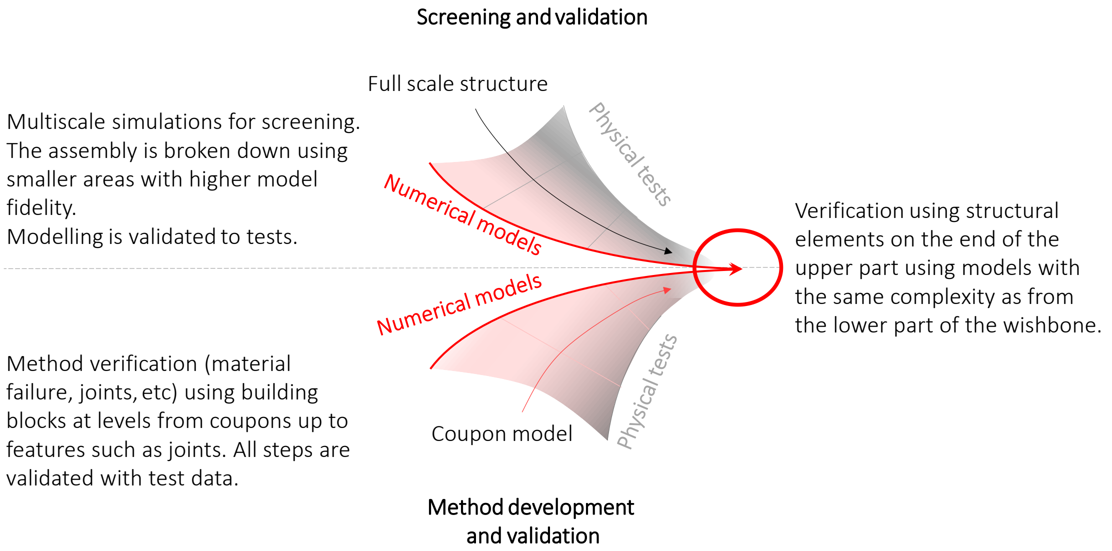


Figure 18. The wishbone framework combines different modelling approaches at different scales for assessment of aerospace structures [58].

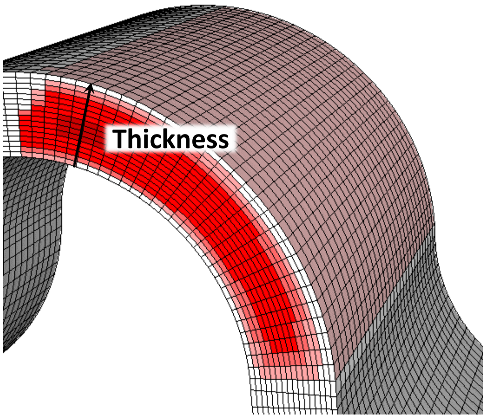
4.3 Challenges for the design of structural composite parts within automotive industry

Compared to the aerospace industry the development cycle is significantly shorter in the automotive industry. Analysis of components made of new materials cannot be based on methods that need to change the PDS that is used but instead need to follow it. This means that parallel testing as performed using the building-block approach [57] on all levels simply cannot be fitted into the workflow. Analysis of composite structures need to follow similar processes as current structures made from metal or polymers.

As both metals and polymers are assumed to be isotropic, both in terms of elastic response and failure, the methods used do not need to take directions into account. Furthermore, failure for these materials is driven by material yielding. Based on this, failure initiation criteria as the maximum principal stress criterion [59] or strain are commonly used within industry or polynomial based criteria, e.g. Azzi and Tsai [28], that take anisotropic properties into account. These criteria are also easy to evaluate based on available results from standard calculations and do not take failure modes into account.

As demonstrated in chapter 1, composite materials with their anisotropic nature, fail in a more complex manner. This means that failure theories, as discussed in section 3.1-3.3, which address individual failure modes need to be accommodated by the analysis methodologies used. The fact that the out-of-plane strength of composite materials is low compared to the in-plane properties, in combination with the fact that complex shapes are common for automotive structures, neglecting the out-of-plane results with traditional shell elements from analysis can be detrimental. Failure due to delamination is not uncommon as a secondary failure since this also is sensitive to defects that are not included in preliminary design. Being able to address such areas is important to be able to design robust structures. An example of delamination failure in a curved geometry is given by Greenhalgh [60] where a failed roll hope for a Formula One car is investigated.

The out-of-plane stress for the corrugated specimen used in **Paper II** is shown in Figure 19 for both traditional shells and solid elements. Here it can be seen that the traditional elements cannot capture the normal stress and out-of-plane failure modes would then be ignored.



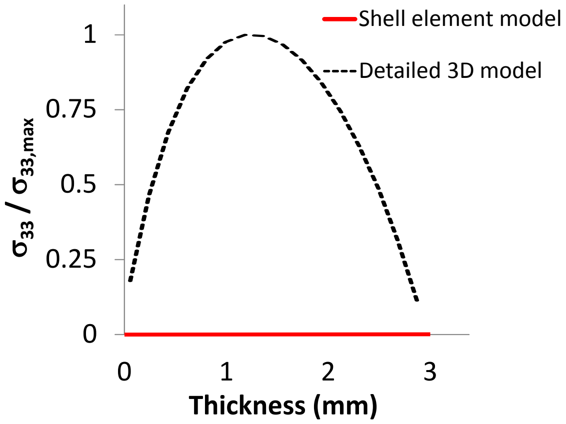


Figure 19. (a) Corrugated specimen for out-of-plane strength measurement. (b) Predicted normal stress through the thickness with traditional shell elements and with solid elements.

4.4 Proposed framework for efficient analysis of composite structures

A framework for the analysis of composite structures needs to be based on results from global FEM with realistic load application, since this is the standard process for analysis today. Moreover, as SotA set of failure initiation criteria are based on 3D stress states and since out-of-plane failure modes need to be addressed, this must also be included in an analysis framework.

From an efficiency point of view, the 3D solid models as used in **Paper II**, are too computationally expensive. Therefore, this modelling approach cannot be used in global models.

An analysis framework that complies with these prerequisites is proposed in **Paper IV**. The ideas within the framework are similar to the Wishbone framework [58], but focuses more on the importance of an automated process for the assessment of structures. The framework is made of three different parts;

- Part A, a global screening part where potential hot-spots are identified.
- Part B, where identified hot-spots are analysed with higher fidelity models.
- Part C, an evaluation part that eases the assessment of several identified hot-spots in a large assembly.

The development of the framework is based on a similar set-up for isotropic polymers [61]. In this work, detailed models are built using tetrahedral elements that can be fitted to any volume and do not have to take a layered structure with orientations into account.

In **Paper IV** the focus is on how the different tasks within each part are automated using commercial software. In this case, pre- and post-processing are performed within Ansa [62] and μetapost [63], respectively.

4.4.1. Screening for hot-spots in global analysis

The screening part, Part A, is developed in Paper **III**. This step uses models similar to those used today in durability analysis, with the exception that composite structures are modelled with second order shell elements. The use of second order elements allows using the Extended 2D FEM approach proposed by Rolfes et al. [64], to predict the full 3D stress tensor based on nodal translations and rotations.

The Extended 2D FEM approach is based on Classical Laminate Theory (CLT), and the assumptions that; 1) the contribution of the membrane forces to the transverse shear strains can be neglected and 2) the displacement modes of the element is cylindrical around the *x*- and *y*-axes of the element [64].

For an arbitrary double curved shell, shown in Figure 20 (a), considering equilibrium, the following system of equations (11-(13) can be established for the transverse shear and out-of-plane normal stresses [65]:

$$\tau_{13,3} + \left[2\frac{\kappa_1}{\lambda_1(x_3)} + \frac{\kappa_2}{\lambda_2(x_3)}\right]\tau_{13} + \frac{1}{\lambda_2(x_3)}\tau_{12,2} + \frac{1}{\lambda_{1(x_3)}}\sigma_{11,1} = 0, \ (x_1\text{-dir}) \tag{11}$$

$$\tau_{23,3} + \left[\frac{\kappa_1}{\lambda_1(x_3)} + 2\frac{\kappa_2}{\lambda_2(x_3)}\right]\tau_{23} + \frac{1}{\lambda_2(x_3)}\sigma_{22,2} + \frac{1}{\lambda_1(x_3)}\tau_{12,1} = 0, \ (x_2\text{-dir}) \tag{12}$$

$$\sigma_{33,3} + \left[\frac{\kappa_1}{\lambda_{1(x_3)}} + \frac{\kappa_2}{\lambda_2(x_3)}\right]\sigma_{33} - \frac{\kappa_2}{\lambda_{2(x_3)}}\sigma_{22} + \frac{1}{\lambda_2(x_3)}\tau_{23,2} + \frac{1}{\lambda_1(x_3)}\tau_{13,1} - \frac{\kappa_1}{\lambda_1(x_3)}\sigma_{11} = 0, \ (x_3\text{-dir}) \tag{13}$$

where

$\lambda_1(x_3) = 1 + \frac{x_3}{r_1}$, $\lambda_2(x_3) = 1 + \frac{x_3}{r_2}$, $\kappa_1 = \frac{d\lambda_1(x_3)}{dx_3} = \frac{1}{r_1}$ $\kappa_2 = \frac{d\lambda_2(x_3)}{dx_3} = \frac{1}{r_2}$, $\tau_{ij,k} = \frac{d\tau_{ij}}{d\text{k}}$ and $\sigma_{ij,k} = \frac{d\sigma_{ij}}{d\text{k}}$.

This system of equations can then be simplified for either single curved shells or flat shells. To do this for arbitrary elements, the radius of an element is calculated based on the nodal positions in **Paper III**. This is shown in Figure 20 (b) for a single curved element, curved around the local x_1-direction.

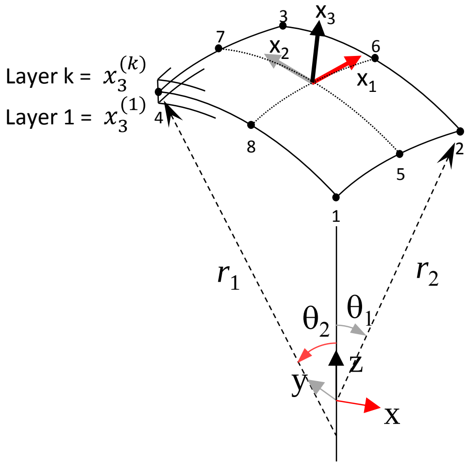


Figure 20. Doubly curved second order shell with constant curvatures, r_1 and r_2, along the main directions of the shell, x_1 and x_2.

Using the Extended 2D FEM approach, the transverse shear stress and normal stress components are predicted through the thickness, based on the nodal translations and rotations. In **Paper III** stress components based on the Extended 2D approach and two solid models with different resolutions in the thickness direction are compared. The stresses are evaluated for a flat $[90_2/0_2]_s$ made from a UD NCF composite material [12] with HTS45 fibres and LY556 resin plate subjected to a double cosine pressure load. Further description of the load case and model can be found in [66].

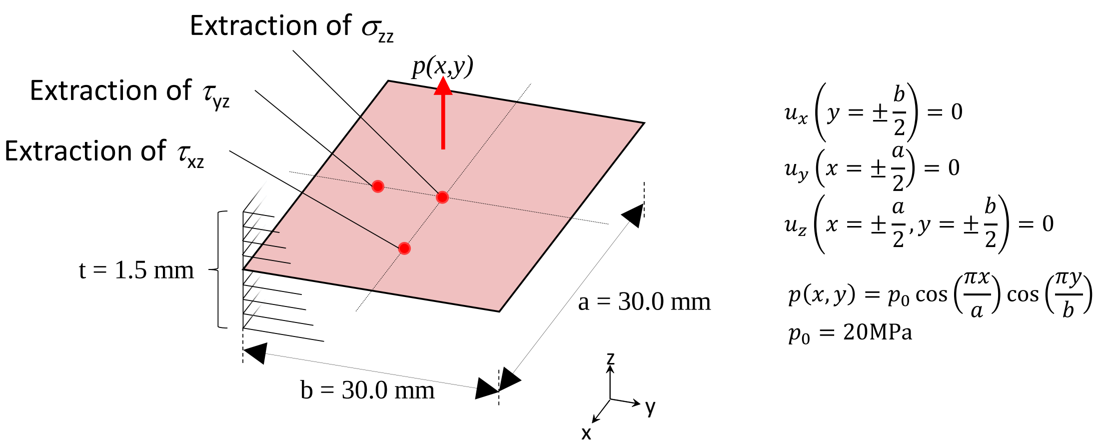


Figure 21. Illustration of composite model and load case for a simply supported plate subjected to a varying pressure load. The locations where the different stress components are extracted are marked with dots.

The resulting stress distributions at different locations, indicated in Figure 21, are shown in Figure 22. Results for the solid models are extracted at the centre of each solid. From this, it can be seen that the Extended 2D FEM approach agrees well with the solid solutions. For the shear components, the stress profile is captured accurately, although the magnitude is underestimated compared to the refined solid model. In [66] some remarks are made upon how predicted failure indices based on stress values from the centre of solid elements compare to values extracted from continuous stress profiles.

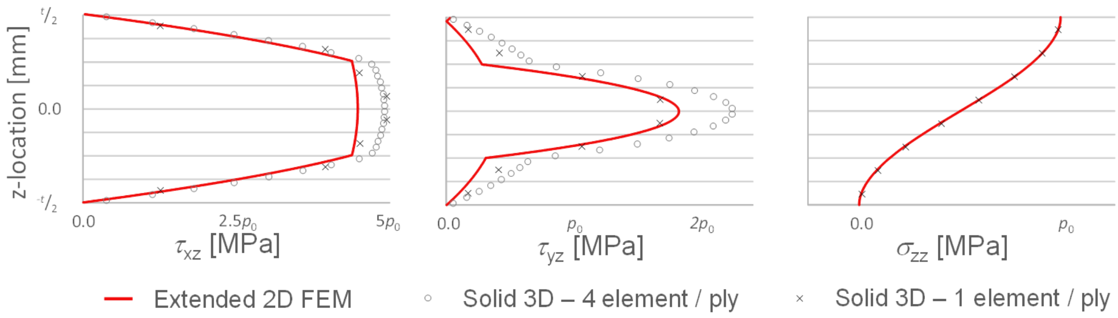


Figure 22. Transverse stress components through the thickness of the loaded plate using the extended 2D FEM approach and solid reference models in [66]. *The horizontal lines represent the ply interfaces. The locations for where the stresses are extracted are marked in Figure 21.*

The validity of the Extended 2D FEM approach on flat and moderately curved profiles, with a radius to thickness ratio of 10 can be found in the literature [67]. This works well for larger structures, but as soon as the geometry becomes more complex, with corner fillets etc., the radius to thickness ratio will rapidly decrease. To address this, a parametric study on the influence of thickness, radius and element size can be found in **Paper III**. The bounds for the study are dimensions that are anticipated for automotive components. The study is performed on an L-shaped test specimen proposed by Jackson and Martin [68], used for interlaminar tensile strength experiments. The specimen is made from UD laminates of AS4/3501-6 composite material [68]. The Extended 2D approach is compared to an analytical solution and solutions from detailed FEM with solid elements. The analytical solution is based on Lekhnistskii's [69] solution for a curved beam segment subjected to end force and moment.

The conclusion of the study is that reasonable accuracy for the 3D stress state can be achieved with the Extended 2D approach. This while using element sizes that are similar to what is used today in global models. This is also validated on a structural element in **Paper III**, where a stiffened panel with T-joints is studied. Using a global model for the geometry, the correct location and failure mode can be predicted, illustrated in Figure 23. Something that is not possible using today's modelling practice, which is also shown.

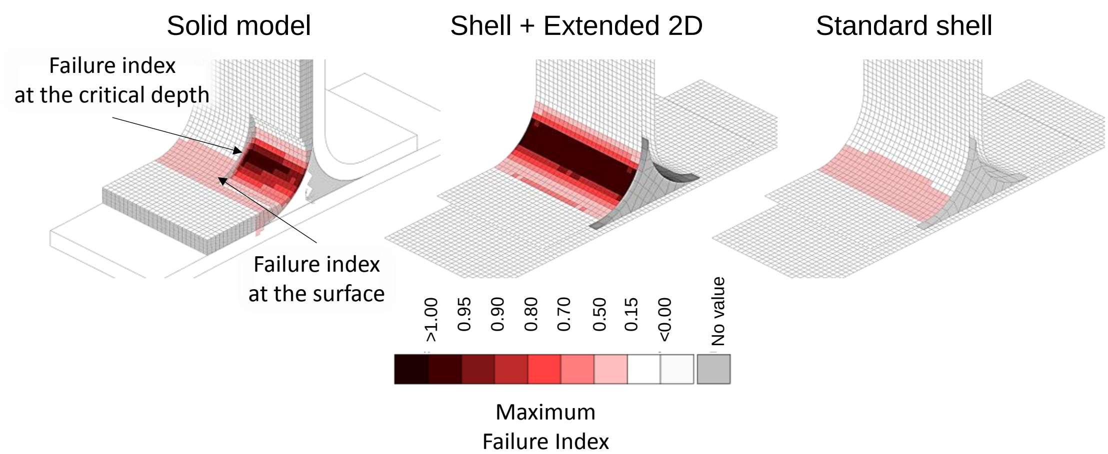


Figure 23. Difference in predicted magnitude and location of failure initiation. Left: Solid model with 3D stress state. Middle: Shell model with extended 2D with a 3D stress state. Right: Standard shell model with 2D stress state.

4.4.2. Local sub-models

Having identified critical locations, hot-spots, using the screening part of the process, the next step is to further analyse these. This part is described in **Paper IV**. To analyse these hot-spots, sub-modelling in Abaqus [49] is used. This technique was introduced in the 90's [70]. As the analyses are intended to predict failure initiation and not take damage propagation into account, it is sufficient to use the solution of the global model to drive the boundaries of sub-models, as long as the boundaries are far enough from the area of interest. The drawback of sub-modelling is the manual process of creating each individual sub-model at the correct location, which quickly becomes a tedious work. In the proposed framework, this work is automated.

The identified hot-spots are exported as coordinates with a proposed size for a spherical sub-model volume. This information is read into the database in the pre-processor, in this case Ansa. Then each sub-model volume is cut out from the geometry in the global model. The remaining midsurfaces are meshed with an element size that will give acceptable solid elements when volumised in the through-the-thickness direction. The layup definition and orientations used for the global model in the laminate are applied to the new shell mesh. Then the elements are volumised according to that definition. The application of boundary conditions is still a manual task since handling connections to other parts, boundaries through complex areas, etc. need the knowledge of an analyst. After this, the model is set up with correct information about the global model and, if needed, user-defined subroutines for failure prediction, and then submitted to the solver. In **Paper IV**, this process is outlined and performed in detail for the test specimen used in **Paper III**, shown in Figure 24, and for an automotive component.

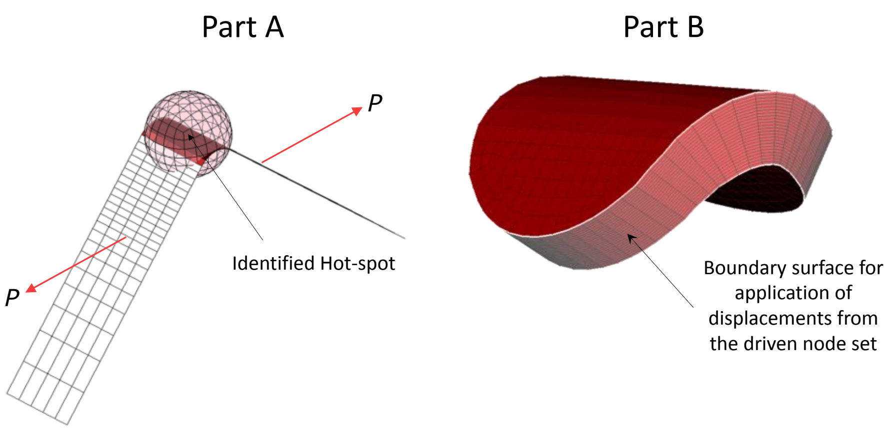


Figure 24. Part A and Part B of the proposed framework. In Part A, the identified hot-spot is shown together with the suggested sub-model volume. In Part B, the suggested sub-model volume is cut out and the local model is built according to the proposed framework with the intersecting surface used to define the boundary conditions for the sub-model analysis.

If the sub-model volume for a hot-spot includes several parts or skin sections, these need to be joined and included. How this can be achieved is discussed in **Paper V**. This is required in order to achieve correct results for the Extended 2D approach when the skin is connected to another part.

The automation of the different tasks for these parts is done with a script for Ansa written in Python.

4.4.3. Post-processing

Part C of the framework is to set up an environment where it is easy to evaluate the structure for the analyst. This is also described in **Paper IV**. Since a design potentially can create a large number of hot-spots, it is important to be able to quickly evaluate if these are critical or not. To achieve this, a Python script for μetapost has been developed. With this script, both the results from the global model and the results from the individual hot-spots are loaded into the same environment. This is illustrated in Figure 25 (a) where both the global and local models are loaded.

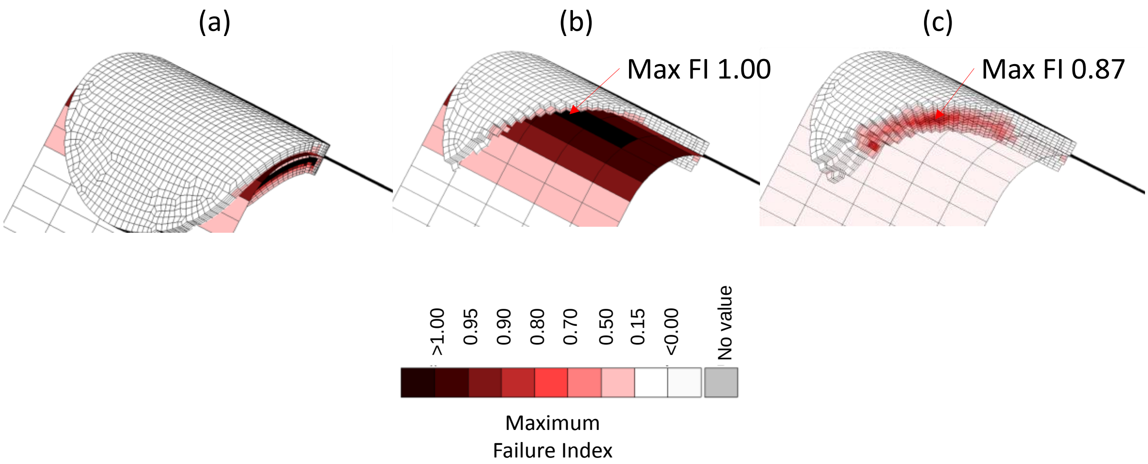


Figure 25. (a) Global model together with sub-model for post-processing. (b) Cropped sub-model to show the global result. (c) Transparent global model to show the result from the local model.

The advantages of this scheme, compared to evaluating each sub-model individually are that it is easier to understand where in space the sub-models are located and to understand their behaviour. With the knowledge of how the global model deforms and its results in that area, as seen in Figure 25 (b), it is easier to understand how the local model behaves and possibly fails, see Figure 25 (c).

4.5 Design and modelling guidelines

With the parametric study that is conducted in **Paper III**, guidelines for how sharp fillet radii that can be evaluated are established. The study was performed on an L-shaped specimen and the accuracy of the Extended 2D FEM approach was compared to an analytical solution based on the model by Lekhnistskii [69]. In this case, the guideline gives recommendations on element sizes in the global model based on inner fillet radius and laminate thickness to achieve a 10% accuracy in the out-of-plane stress prediction compared to an analytical solution, as illustrated in Figure 26.

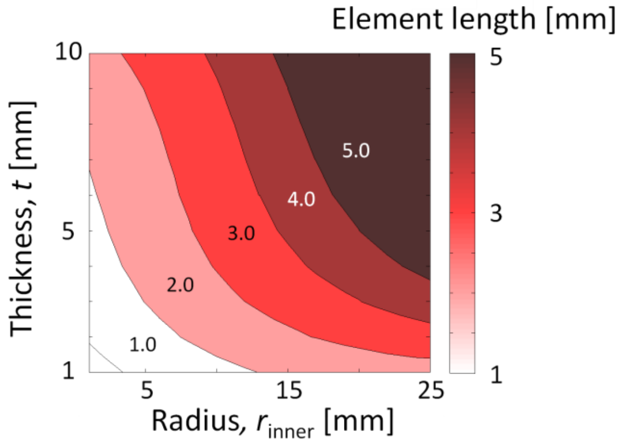


Figure 26. Element size needed to achieve accuracy within 10 per cent of σ_{33} for the extended 2D FEM approach compared to the analytical solution, as a function of inner radius and thickness.

5 Summary of appended papers

This work has been performed with the ambition to provide the automotive industry with the ability to efficiently and reliably design automotive composites parts. For this purpose the thesis aimed at answering the following research questions:

- RQ.1. What are the failure modes in orthotropic Non-Crimp Fabric (NCF) composite materials and how should they be predicted?

- RQ.2. How should a framework for efficient and reliable strength analysis of automotive composite structures be constructed?

Knowledge of the materials likely to be used in the automotive industry is fundamental to build a framework for reliable analysis. Studies on how failure initiates in NCF reinforced composite materials and how to predict it are presented in **Paper I** and **Paper II**.

With knowledge of the NCF composite materials, and the ability to predict failure initiation, existing CAE tools and methods are assessed for their applicability to these materials. Available tools are evaluated with respect to their efficiency in the analysis of large structures. Identification of performance gaps in existing codes and development of a robust and efficient computational framework for the analysis of large composite structures are performed in three papers, **Paper III-V**.

The papers and their contributions to an efficient framework for durability analysis of primary automotive composite structures are illustrated in Figure 27. The appended **Papers I-V** comprise studies towards a computational framework for the analysis of orthotropic composite materials in an automotive industrial context. The tools and processes used are to a large extent available in commercial tools already used in the automotive industry. Identified gaps are overcome by the development of user subroutines for commercial software and scripts in Matlab and Python.

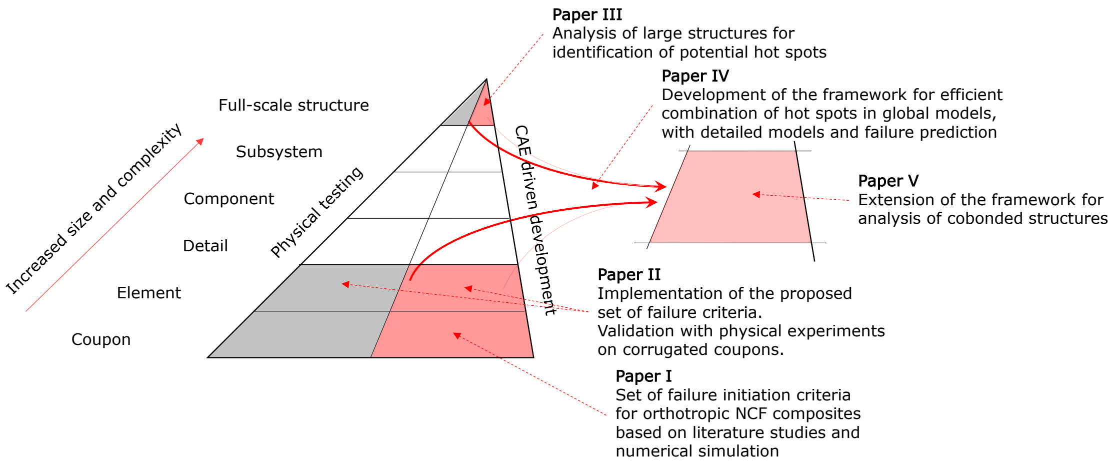


Figure 27. Illustration of how the included papers fit into developing an efficient analysis framework.

In **Paper I**, findings from the literature on failure in NCF composite materials are enhanced. The existing modes for transverse failure in orthotropic NCF composite materials are identified. In addition to the failure modes that are active in UD composites, orthotropic NCF composite materials also have an interbundle failure that appears under out-of-plane loading. Based on these insights, a physically motivated set of failure initiation criteria is proposed. The set of failure criteria is based on failure modes for UD materials and extended with the interbundle failure mode in NCF composite materials. The criteria are to be used on the laminae level with associated properties. To verify the findings from the literature, numerical studies are performed to investigate how ply bundle shape, temperature change during manufacturing and properties of constituents affect the shape of the predicted failure envelopes. These studies are performed using FE models of typical RVE for a UD NCF composite material.

Numerical implementation of the proposed set of failure criteria for orthotropic NCF composite materials is reported in **Paper II**. The implementation is done in the FE software Abaqus as a user output variable UVARM, which is calculated for each material point in the model. The implementation is done at the ply level since the set of criteria depend on the full 3D stress tensor. Validation of the failure criteria is performed with physical experiments on corrugated coupons made from HTS45/LY556 UD NCF composite material. The coupons are loaded to failure initiation under out-of-plane stresses. The proposed set of failure criteria is compared to SotA failure modes for UD materials. From the validation, it is found that the proposed failure criteria give accurate predictions.

In **Paper II**, the already established fact that measurements of the out-of-plane properties are very difficult is confirmed. Comparing results from the tests performed on corrugated specimens to data found in the literature for other test specimens clearly shows that the out-of-plane failure is dependent on manufacturing defects and size effects of the loaded region.

Paper III addresses how large automotive composite structures, typically modelled with shell elements, can be analysed. As traditional shell elements only consider in-plane stress components, failure modes associated with out-of-plane loads may be overlooked, and potentially devastating. To overcome this, the Extended 2D FEM approach proposed by Rolfes et al. is used together with the stress-based failure criteria proposed in **Paper I** and implemented in **Paper II**. The validity of the approach is studied numerically for geometric dimensions, in terms of curvature and thickness, relevant for the automotive industry. The study gives guidelines on how to model different geometries to reach a certain tolerance in the predictions of the out-of-plane strength. It is shown that the proposed method allows for efficient screening of strength criticality for large automotive structures.

With the knowledge of how failure can be predicted in detailed models and the capability of predicting potential hot-spots, an automated framework is outlined in **Paper IV**. The steps needed for the global analysis, creation of higher fidelity models at critical locations using the sub-modelling technique, and setting up an environment for the analysis of the detailed sub-model are presented. The process is then employed on an automotive structure.

In **Paper V**, the process is extended and tested on an assembled structure. As composite parts often are co-cured or joined, it is important to be able to accurately predict critical locations both during hot-spot screening and in subsequent detailed analysis. In this study, important aspects for building and analysing such structures are discussed.

6 Discussion

6.1 Validation of failure initiation criteria

Understanding failure initiation in composite material requires a lot of data from experimental tests to cover different loading conditions. Meso-scale modelling proved to be an efficient tool to complement the physical experiments with numerical simulations. The used method with superimposed loads gives a quick tool that can be used to gain insight into how a composite reinforcement behave. In this work, knowledge of how geometrical aspects of real bundle shapes can affect strength properties by introduction of local stress concentrations was gained. This can be of importance in early phases when material systems either are designed or evaluated.

6.2 Accuracy of the proposed framework

The proposed set of failure initiation criteria is validated for a single type of NCF composite material and a limited number of geometries. As the initiation criteria are based on the physical behaviour of the material system it should be valid for other types as well, i.e. multi-layered NCF mats with other stitching patterns. However, it is important to measure the allowable needed in the failure criteria on similar geometries that are intended to be used. This since the measured values will differ between material systems and between manufacturing methods.

The methods used in the proposed framework are tested with numerical models to understand the relationship between accuracy and modelling resolution for simple geometries. As the Extended 2D method is tested on its own for more complex geometries, and the foundation for it allows for more complex geometries, it is assumed to be valid. However, until a supporting implementation for doubly curved geometries exists, care needs to be taken for such geometries. Once this is developed, guidelines need to be established concerning the modelling of such geometries, similar to what has been done for single curved geometries.

6.3 Applicability of the proposed framework

During the development of the framework, focus has been on primary composite structures made of NCF composites within the automotive industry. As the framework is built from a number of blocks for solving different tasks, each of these blocks may be substituted as long as the input and output to that block are kept. The first thing that is easily exchangeable is the set of failure initiation criteria. If other material systems are used, then this could easily be exchanged to another, e.g. a criterion for another material system or a criterion that better suits an industry standard, as may be the case in aerospace.

Even if the framework is implemented into the Beta software environment for pre- and post-processing, and using Abaqus as the FE solver, the same process can be adapted in other software environments. The framework mainly is built from tools readily available for pre- and post-processing of composite models and using solution techniques available in many commercial solvers.

As most OEMs within the automotive industry have access to a broad portfolio of software it is not a serve limitation that software from more than one supplier is used. However, for smaller companies, this could be a challenge and it will be beneficial to have the complete framework included in one software suite. Moreover, access to a CAE based framework for the assessment of composite structures would decrease the threshold for other industry sectors to start using composite materials in structural components.

The ability to easily estimate failure initiation with an efficient analysis framework is not only beneficial for the automotive industry. As composite design is driven often by physical testing, it is hard to predict and analyse potential secondary failure locations and failure modes. A CAE based framework that can predict potential hot-spots can be used in all industries that use composites in their primary structures.

7 Conclusions

Ability to accurately predict failure initiation with numerical models is essential for successful utilisation of the superior specific properties that composite materials offer. The research in this thesis contributes to:

- Understand failure initiation in NCF reinforced composite materials, which show orthotropic properties. The importance of taking real geometry into account when studying meso-models as stress concentrations from non-uniformities can otherwise be missed. How manufacturing temperature and constituent properties affect the failure mechanism is also studied.

- Better failure initiation prediction in NCF composite materials with a proposed set of failure initiation criteria for NCF composite materials that show a weaker out-of-plane strength compared to transversely isotropic materials. The set of failure initiation criteria is physically based on the failure modes observed in the composite material.

- A framework for efficient analysis of large and/or complex composite components in primary structures. The applicability within the automotive industry for established methods in literature are explored. These methods are then put into a framework that allows for efficient analysis.

7.1 Future work

In the previous discussion, the proposed set of failure initiation criteria and the proposed framework for analysis gives a good starting point for efficient analyses of complex primary automotive composite structures. Finding limitations to the current set-up and how to improve the robustness of the methods and criteria is valuable.

NCF composite materials

The proposed failure criteria are developed and tested based on studies of UD NCF composite materials. Failure of other NCF systems, e.g. quasi-isotropic multi-layered fabrics, needs to be studied. This to investigate if the same failure modes prevail and thereby the set of failure initiation criteria is appropriate.

Implementation in commercial code

Although the proposed framework is developed and implemented in commercial software there are still parts that use Matlab. This mainly concerns the implementation of the Extended 2D Approach and calculation of failure initiation in global models. The drawback of this is that both the use and the computations become more time consuming as data needs to be transferred between different software. Also, maintenance of in-house codes to keep them up to date with changes in other software is time consuming.

Estimation of material properties

SotA failure initiation criteria are often based on allowable stresses. As already noticed in **Paper II** and in the literature these can be hard to measure or need to be measured at specimens similar to what is used in the design. Finding other means of evaluating failure initiation, e.g. based on energy release, could yield more robust allowable values.

However, estimating energy release from global models, i.e. shell models, has proven to be a delicate task.

Correlation to experiments

The proposed framework is based on methods not yet applied to automotive structures and compared to physical tests. Therefore more experimental data is needed to establish limitations on what designs the proposed methods are valid for. Numerical parametric studies as performed in **Paper III** give a first guideline. However, more complex geometries, such as double curved structures should be explored and effects from manufacturing should be included in such guidelines.

Fatigue aspects of polymer composites

The research presented in this thesis focus on durability aspects and failure initiation in particular. Further studies on how fatigue should be included will be needed as structures like the BIW and other structural parts must endure the full vehicle life.

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Glossary

ABAQUS	FE solver.
Ansa	Pre-processor for FE models.
BEV	Battery electric vehicle. A term for clustering cars with batteries as only storage of energy.
BIW	Body in White, assembled car body before painting and marriage with engine and sub-assemblies.
C-class	Medium cars.
CAE	Computer aided engineering.
CFRP	Carbon fibre reinforced composite.
Critical ply	The ply, in a laminate, that is the most critical, having the highest Failure Index.
Coupon	Test specimen for material characterisation.
D-class	Large cars.
DFRP	Discontinuous fibre reinforced polymer.
E-class	Executive cars.
Failure index (FI)	Index that relates the applied load to the allowable load.
Failure mode	The mode of failure that is most likely to occur under the acting stress state.
Fracture plane angle	The angle at which failure is most likely to occur under the acting stress state.
FEM	Finite element analysis; a numerical tool for structural analysis.
FRP	Fibre reinforced polymer.
GFRP	Glass fibre reinforced composite.
Isotropic	Material with identical properties in all three perpendicular directions.
Kerb weight	Total weight of car including necessary consumables, e.g. oil, coolant, fuel etc., and driver.
Lamina	A single layer of a composite material, also called ply.
Laminate	All laminae stacked on top of each other makes a laminate.
Lay-up	Order of laminae within a laminate.
ICE	Internal combustion engine. A term for clustering cars with traditional combustion engines.
ILSS	Interlaminar shear strength.
In-situ	Variation of a property due to the position within a laminate.
NCF	Non crimp-fabric.
Orthotropic	Material with different sets of properties in all three perpendicular directions.
PDS	Product development system.
Pre-preg	Pre-impregnated composite material. The fibres are impregnated with the matrix material.

Range anxiety	Fear that a vehicle has insufficient range to reach its destination, thereby stranding the occupants.
RTM	Resin transfer moulding. A manufacturing process where resin is injected into a mould with dry fibres.
RVE	Representative volume element.
SFRP	Short fibre reinforced polymer.
SMC	Sheet moulding compound. Ready to mould composite material for compression moulding.
SotA	State of the art.
Thermoset	Plastic material that is crosslinked and cannot be reshaped at elevated temperatures.
Thermoplastic	Plastic material that is not crosslinked and can be reshaped at elevated temperatures.
Transversely isotropic	Material with one set of properties in one direction and another set of properties in the transverse plane.
UD	Uni-directional material. Composite with fibres in one direction.
UMAT	User material in ABAQUS as a subroutine.
UVARM	User defined variable at each material point in an FE model in ABAQUS as a subroutine.
µetapost	Post-processor for FE results.

Nomenclature

C	Crimp, a measure of waviness.
l_{y}	Length of the yarn in a fabric.
l_{f}	Length of fabric.
l_{elem}	Length of finite element.
σ_{AA}	Stress in the AA-direction. A can be 1, 2, or 3.
τ_{AB}	Shear stress in the AB-direction. A and B can be 1, 2, or 3 and A ≠ B.
$\sigma_{AA,C}$	Stress derivative of the AA-direction with respect to the C direction. A and C can be 1, 2, or 3.
$\tau_{AB,C}$	Shear stress derivative of the AB-direction with respect to the C direction. A, B and C can be 1, 2, or 3 and A ≠ B.
X_{T}	Basic strength in tension in the 1-direction.
X_{C}	Basic strength in compression in the 1-direction.
τ_{T}	Transverse shear on the fracture plane.
τ_{L}	Longitudinal shear on the fracture plane.
σ_{N}	Normal stress on the fracture plane.
S_{T}	Transverse shear strength.
S_{L}	Longitudinal shear strength.
η_{T}	Transverse friction parameter.
η_{L}	Longitudinal friction parameter.
Y_{T}	Basic strength in tension in the 2-direction.
Y_{C}	Basic strength in compression in the 2-direction.
m	Reference to the misaligned coordinate system for fibre kinking.
is	In-situ.
Z_{T}	Basic strength in tension in the 3-direction.
Z_{C}	Basic strength in compression in the 3-direction.
$ILSS$	Interlaminar shear strength.
$FI_{F,T}$	Failure index for failure along the fibres (F) in tension (T).
$FI_{M,C}$	Failure index for transverse matrix failure (M) in compression (C).
FI_{M}	Failure index for transverse matrix failure (M).
FI_{KINK}	Failure index for kinking failure (KINK). Failure mode that occurs along the fibres under compressive loading.
$FI_{M,B}$	Failure index for transverse matrix failure (M) inside the fibre bundle (B), intralaminar failure.
$FI_{M,MI}$	Failure index for transverse matrix failure (M) in the matrix interface (MI), interlaminar failure.
α	Fracture plane angle.
α_{0}	Fracture plane angle under pure compression.
E_{AA}	Stiffness in the AA-direction. A can be 1, 2, or 3.
G_{AB}	Shear stiffness in the AA-direction. A can be 1, 2, or 3.

ν_{AB}	Poisson's ratio in the AB-direction. A and B can be 1, 2, or 3 and A $\neq$ B.
α_{AA}	Coefficient for thermal expansion in the AA-direction. A can be 1, 2, or 3.
κ	Curvature value. Calculated as 1 over the radius. ($^1/_{radius}$)
λ	Location parameter through the thickness.
λ_i	Location parameter through the thickness taking the radius about the *i*-direction into account.
κ_i	Derivative of the location parameter λ_i through the thickness with respect to the thickness direction.
P_1	Point on second order element used for calculation of element radius.
P_2	Point on second order element used for calculation of element radius.
P_3	Point on second order element used for calculation of element radius.
s	Vector for calculation of element radius.
t	Vector for calculation of element radius.

Paper I

Orthotropic criteria for transverse failure of non-crimp fabric reinforced composites

Molker, H., Wilhelmsson, D., Gutkin, R. & Asp, L. E.

Journal of Composite Materials. 50(18), pp.2445-2458, 2015

doi: 10.1177/0021998315605877

Paper II

Implementation of failure criteria for transverse failure of orthotropic Non-Crimp Fabric composite materials

Molker, H., Gutkin, R. & Asp, L. E.

Composites Part A: Applied Science and Manufacturing. 92, pp.158-166, 2016

doi: 10.1016/j.compositesa.2016.09.021

Paper III

Hot-spot Analysis in complex composite material structures

Molker, H., Gutkin, R., Pinho, S. & Asp, L. E.

Composite Structures. 207, pp 776-786, 2019

doi: 10.1016/j.compstruct.2018.09.088

Paper IV

Industrial framework for identification and verification of hot-spots in automotive composite structures

Molker, H., Gutkin, R. & Asp, L. E.

Submitted Manuscript

Paper V

Verification of hot-spot in complex composite structures using detailed FEA

Molker, H., Gutkin, R. & Asp, L. E.

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Accurate failure prediction of components is vital during the design process. Introduction of continuous carbon fibre composite materials in primary structural automotive components needs efficient analysis methods. The anisotropic nature of composite materials and the complex geometries causes stress states and potential failure modes that cannot be captured with the models traditionally used in the automotive industry.

In this thesis two different aspects are studied, first how failure in Non-Crimp Fabric (NCF) materials can be predicted, secondly how an efficient analysis framework should be designed.

Initially failure in NCF materials are studied and a new set of failure initiation criteria is proposed. This takes the orthotropic nature into account and addresses an additional interlaminate failure mode in the out-of-plane direction.

With the knowledge that all stress components are important to be able to predict all possible failure modes, an analysis framework for large primary structures is proposed. The framework is mainly based on methods available in commercial tools to make the implementation into a product development system as easy as possible.

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